

NOTES ON THE METEORITE OF ESTHERVILLE, IOWA, WITH ESPECIAL REFERENCE TO ITS INCLUDED "PECK- HAMITE" AND PROBABLE METAMORPHIC NATURE.

By GEORGE P. MERRILL,
Head Curator of Geology, United States National Museum.

This meteorite, both on account of its unusual lithological nature and the number of individuals composing the fall, has been the subject of numerous papers and much study.

It will be recalled that the first description was by Prof. S. F. Peckham,¹ who briefly noted that the stony portion consisted of dark green crystalline masses some of which "are two inches in thickness and exhibit a distinct monoclinic cleavage." This mineral he did not further identify, but stated that thin sections of the stone under the microscope showed the presence of olivine and a triclinic feldspar embedded in a matrix of pyroxene. Shepard² noted the occurrence of chrysolite in large masses, some showing imperfect crystalline facets and an eminent cleavage. He also noted a "feldspathic mineral, presumably anorthite" and an "opal-like mineral of a yellowish brown color, probably chassignite." No mention was made of any pyroxenic constituent. Smith's investigations³ were much more elaborate. He determined the presence of bronzite and olivine, the latter in masses "of from one-half to one inch in size, having an easy cleavage, especially in one direction." He also examined the opalescent silicate mentioned by Shepard, and by analysis found its composition as in column I on the next page, which is, he said, "equivalent to $\text{Si}\bar{\text{R}}_2 + \bar{\text{S}}_2\text{i}\bar{\text{R}}$, or one atom of bronzite plus one atom of olivine, a form of silica that we might expect to find in meteorites." In a second paper he announced a further investigation of the opalescent silicate, which he described as having a dingy yellow color and a fused surface. When broken it showed a greasy aspect, with a more or less perfect cleavage and a structure differing widely from olivine. A second analysis yielded as in column II.

¹ Amer. Journ. Sci., vol. 18, July, 1879, pp. 77-78.

² Idem, vol. 18, Sept. 1879, pp. 186-188.

³ Idem, vol. 19, 1880, pp. 459-463, and 495; vol. 20, 1880, pp. 136-137.

	I	II
	Per cent.	Per cent.
Silica (SiO ₂).....	49.50	49.59
Ferrous oxide (FeO).....	15.88	17.01
Magnesia (MgO).....	33.01	32.51
	98.39	99.11

These closely agreeing results he felt justified him in considering the mineral a new species, to which he gave the name *Peckhamite*. S. Meunier¹ also studied the meteorite, recognizing the presence of olivine, bronzite, and a triclinic feldspar, and suggested that Smith's peckhamite was not a new mineral species, but a result of "the union of alternate laminae of extremely thin bronzite and olivine." Tschermak,² who studied the stone in thin section, recognized the occurrence of olivine, bronzite, and plagioclase. The bronzite he described as having in part the usual appearance, with few inclusions, and in part as clouded by fine dust and showing large glass inclusions. These turbid grains he assumed were of the same nature as Smith's peckhamite, which he described as showing the prismatic cleavage of bronzite, but giving also cleavages which could be referred to the crystal faces of olivine. The optical characters were described as almost similar to those of bronzite. "The whole section," he wrote, "is clouded by a fine dust and also contains larger inclusions of two kinds. One variety is in the form of dark brown to black spheres, the other rod-like or spindle-like colored glass inclusions which correspond to negative crystals and similarly colored round glass inclusions. A glance suffices to show that the substance is a mixture, and the analysis does not give me a result which corresponds to a single mineral." He concluded as a result of his studies that the so-called peckhamite was a bronzite rendered turbid and of a glassy luster by a great quantity of inclusions. In this he was apparently correct. Wadsworth, who was the last to publish the results of a microscopic examination, reported the presence of diallage in addition to the other minerals mentioned, and agreed with Tschermak as to the nature of the peckhamite.

My own investigations were instigated by an examination of a fragment of the stone in the Shepard collection, around one portion of which had been painted a yellow ring, indicative of some unusual feature to which evidently it was wished to call attention. Examination showed this ring to include a yellow-brown, opalescent mineral which it was at once apparent was the original mineral called *chassignite* by Shepard, and *peckhamite* by J. L. Smith. The unusual appearance of this mineral was sufficient to warrant further investigations, the results of which are given below.

The pyroxenic constituents of the stone are of more than ordinary interest and were the first to receive attention. Examination with a

¹ Compt. Rend., vol. 94, 1882, pp. 1659-1661.

² Photographien, pp. 22 and 23.

pocket lens, or even in many cases with the unaided eye, shows the mineral in two distinct phases—1, a green, highly lustrous form in crystals up to 50 mm. in length, with very evident cleavage, sometimes showing a greasy or opalescent luster; 2, the yellow-brown or opalescent phase without crystal form but very evident cleavage, forming the peckhamite of Smith. This last occurs sometimes in globular and pebblelike forms which show up on a broken surface in a manner suggestive of the perlitic structure of some rhyolitic glasses and again in partially filled cavities, sometimes forming a coating on the interior wall not more than a millimeter or so in thickness, presenting on the inner surface a botryoidal structure such as is common to minerals deposited from solution, as silica, or limonite in geodic form. The two phases, though often in close juxtaposition, are so widely variant that separations and analyses of each were undertaken, with the results given below.

	1	2	3		4	5
	Peckham- ite.	Ensta- tite.	Peckham- ite.		Ensta- tite.	Peckham- ite.
Silica (SiO_2)	53.04	54.24	49.545	.....	54.12	54.54
Alumina (Al_2O_3)	2.80	3.07	.....	.....	.03	.53
Ferrous oxide (FeO)	14.88	13.98	16.445	.....	21.05	12.73
Ferric oxide (Fe_2O_3)	.66	.....	.....	\text{Cr_2O_3	Trace.	.....
Titanic oxide (TiO_2)	.12	.16	.....	Alks.	.09	.....
Magnesia (MgO)	28.58	28.42	32.76	.....	24.50	31.19
Lime (CaO)	None.	None.	.....	.....	.....	0.87
Manganese (MnO})	.....	.14	.....	.....	.....	Trace.
	100.08	100.01	98.750	.....	99.79	99.86

Not being satisfied to let pass the apparent lack of agreement in the peckhamite analyses by Whitefield (column 1) and Smith (column 3), a second sample was taken from a pebble-form inclosure some 2 centimeters in diameter in the large mass of this meteorite in the Yale University collections. This yielded Mr. E. V. Shannon, of the Department of Geology in the United States National Museum, the results in column 5. It will be noted that this last differs from Whitfield's analysis in showing an increase of 1.50 per cent silica (SiO_2) and 2.61 per cent magnesia (MgO) and a decrease of 2.15 per cent ferrous oxide (FeO). Also in carrying a small amount of lime. Inasmuch as I have no reason to doubt the accuracy of either of these analyses, I am led to the conclusion that the mineral, itself an alteration product, is somewhat variable. I confess, however, to having difficulty in accepting Smith's results (column 3) on the same terms. It is to be noted incidentally that both Whitfield's and Shannon's agree fairly well with those of the enstatites of the Lodhran and Ibbenbühren meteorites as given by other workers. The two analyses of enstatite as

given by Whitfield and Smith agree much more closely than do those of peckhamite, the chief difference being in the proportional amounts of iron and magnesia.¹

It should be mentioned in this connection that the material in analyses 1, 2, and 5 was carefully assorted and examined under the microscope to assure its purity. The enstatite phase (column 2) was of a bright greenish color, limpid, and almost free from inclosures of any kind. (See fig. 1, pl. 22.) The peckhamite phase (columns 1 and 5) of a yellow-brown hue was so clouded by innumerable empty cavities and inclosures as to be only translucent. (See fig. 2, pl. 22.)

Our results thus far then agree with Tschermak. I may add here, however, that I can not understand the statement of Smith and others relative to a mineral of an olive-green color occurring in masses of from one-half to 1 inch in diameter, having an easy cleavage, especially in one direction, which is identified as *olivine*. I have made repeated examinations of the mineral corresponding to this description and found it in every case to be mainly enstatite, though often intergrown with small amounts of *olivine*. Analysis 2 on page 365 is of material from one of these crystals carefully freed from possible admixtures with *olivine* by hand picking and boiling hydrochloric acid and sodium carbonate solutions.

Equally or more difficult of comprehension is his statement that the soluble portion of the stone is "without a trace of lime, thus indicating the absence of anorthite." I find this mineral more or less abundant in every slide examined, and the solution obtained by even a short digestion of the powdered stone in dilute hydrochloric acid yields an abundant precipitate of this constituent. It is, of course, possible that working with a very small amount of material (a fault altogether too common) he may have had a feldspar free sample, but an inspection of the figures on plate 23 must convince one of the insufficiency of such an explanation.

None of the writers quoted note the presence of a calcium phosphate, though the stony portion, when powdered and treated with acid ammonium molybdate, yields abundantly the customary yellow precipitate. I have not been able to determine the mineral by its optical properties alone, but when an uncovered slide is treated with a drop of the molybdate solution sundry areas occupied by an irregular and optically indistinct colorless mineral gradually dissolve out, leaving minute cavities and yielding abundant globules of ammonium phosphomolybdate. The presence of a monoclinic pyroxene, the diallage of Wadsworth, is abundantly confirmed.

¹ It may be remarked that as Smith's analysis was that of the "insoluble" silicate portion and apparently not examined microscopically it might naturally be expected to contain an admixture of diallage and other impurities. That it does not is but one of the several puzzling things in his work.

The above-described features, with sundry others to be noted, are suggestive of conditions through which the meteorite has passed, which have not received recognition by previous writers and which will, therefore, be considered in some detail here.

One of the most striking features of the stone on casual inspection is its slag-like appearance, even in the interior portions. This was noted by Von Rath,¹ who describes it as highly remarkable on account of the numerous cavities, upon the walls of which small individual (and obviously secondary) crystals have formed. Smith also in his description wrote:²

Another striking feature in the relation of the iron and stony matter is that the larger nodules of iron seem to have shrunk away from the matrix, an elongated fissure of from 1 to 3 mm. sometimes intervening, separating the matrix and nodules to the extent of one-half the circumference of the latter and appearing as if the iron had contracted from the stony matrix during the process of cooling. There are numerous small cavities of various sizes where there are no iron nodules, and where the minerals appear more crystalline, indicating an irregular shrinkage during the consolidation.

No other explanation is, however, attempted.

An examination of the stone in thin sections brings out at once the fact that though the ground is holocrystalline few of the larger constituents present outlines to suggest that they result from crystallizing freely from a molten magma. (See figs. 3, 4, and 5, pl. 22.) Both the pyroxenes—enstatite and "peckhamite" occur in angular or rounded pebble forms, as does also the diallage, and as shown in plate 23. It is obvious, too, I think, that quite aside from this, two minerals similar in composition but dissimilar in color and physical characteristics, as are the first mentioned, could not both have originated from the cooling of the same magma and in the positions they now occupy (figs 3 and 4, pl. 22). It is to be noted further that the larger masses of olivine, or pyroxene, whichever they may be, have a distinct fragmental or pebble-like aspect.³ (See Nos. 1, 2, and 3 on pl. 24.) That of the "peckhamite" in the Yale specimen and in the slice belonging to the University of Minnesota is also unmistakable.⁴ These forms often show on a polished surface numerous fine points of metal which are lacking in the granular ground in which they are imbedded and which serve to still further differentiate them.

The form and crystallographic condition of the feldspathic constituents are often peculiar. Two distinct forms are recognizable in the rock, the one occurring in fairly large plates for the most part clear of inclosures, limpid and with extremely irregular outlines

¹ Verhandl. Natur. Hist., Vereine, Bonn., vol. 37, 1880, p. 239.

² Amer. Journ. Sci., vol. 19, 1880, pp. 559-463.

³ One of these pebble forms in the Yale University specimen is 8 cm. in greatest diameter.

⁴ Smith notes in his description of the mineral that "small rounded nodules, several millimeters in size, are found in the interior of the mass, sometimes of irregular form," etc.

(pl. 23). These often show the broad twin laminae characteristic of anorthite—with which species they seem to agree optically—and are readily soluble in hydrochloric acid. This at times is strongly suggestive of the well-known maskelynite type, into which it, indeed, seems to grade and of which I am at times inclined to regard it as an unusual phase. The second occurs in the usual lath-shaped forms characteristic of basic eruptives, and is unquestionably the result of crystallization in place if not a direct secretion from a molten magma. It is to the larger forms that attention needs particularly to be called. Their most striking features are the irregular outlines referred to above. These, as will be noted by reference to the figures, extend outward into all the minute interstices of the other silicates, often in such minute ramifications as to show that they were the last constituent to solidify from a very liquid magma.

In numerous instances the interior of a crystal is clouded by inclosures and bubbles. Figure 3 shows a marked example of this. In such cases extinction is simultaneous and uniform for the most part over border and nucleal portion alike. In Figure 3, on Plate 23, especially referred to, the colorless border, it will be noted, includes small crystals of pyroxene and perhaps olivine, their small size preventing an exact determination, as their optical properties are obscured by their host. The first thought that arises on seeing these peculiar forms is that of secondary enlargement. But for the fact that the olivine and pyroxene both fuse at a somewhat lower temperature than the feldspars, one might consider these borders as products of a metamorphism due to a rise in temperature, a view sometimes held regarding the maskelynite in chondritic stones. Attention should also be called to the elongated bubbles or cavities extending from nucleal portions out into the clear border in the upper left as the figure is oriented in the plate. In a few instances inclosures in the border were noted, which it was thought from their lack of color, form and occasionally characteristic fracture may be apatite. Here again optical properties are obscured by the host.

The facts presented above, together with the general linear arrangement of the cavities and their secondary minerals, and the peculiar slag-like condition of the mass as a whole, lead me to consider the Estherville meteorite as a product of metamorphism—a stone originally consisting of fragments of the various silicates noted which has been subjected to such compression, heating, and reducing vapors as to render the more finely disintegrated material holocrystalline. Incidentally it has become impregnated with metal resulting from the reduction of some preexisting ferrous mineral. That this may have been a chloride (lawrencite) is possible, but if so the mass has suffered shrinkage, since this mineral would yield, theoretically, but 44.1 per cent of metal. The peculiar sponge-like

character of the latter suggests, however, that it was in a sufficiently liquid form to permeate the siliceous matrix in all directions, and hence the existing cavities may convey little idea of the original amount of shrinkage. However this may be, the facts given, as a whole, seems to show that the Estherville meteorite is a metamorphic rock.¹

My purpose in giving this detailed description of this more than ordinarily interesting meteorite is not merely to show the chemical and petrographic nature of the stone as it is to-day. I have felt for some years that in the discussions of the origin of meteorites too little attention has been given to their composition as compared with terrestrial rocks, and to their "life histories," if I may be allowed the expression, as revealed by a detailed study of their primary structural features and those which have been induced by secondary causes.²

If it can be shown that certain conditions must have prevailed to produce existing results, while this may not point to a definite source of origin for the body, it will at least narrow the field of speculation and can in the future lead to more definite conclusions than have many of the theories and guesses proposed in the past.

For the privilege of examining and, in some cases, obtaining material for analysis, the author is indebted to Prof. J. E. Wolff, of Harvard University; Prof. Edward Wigglesworth, of the Boston Society of Natural History; Prof. E. S. Dana, of Yale University; Dr. E. O. Hovey, of the American Museum, New York; and Prof. W. H. Emmons, of the University of Minnesota.

EXPLANATION OF PLATES.

PLATE 22.

ESTHERVILLE, IOWA, METEORITE.

- FIG. 1. Cleavage fragments of enstatite showing character of material analyzed.
 2. Cleavage fragments of peckhamite showing character of material analyzed.
 3. Section showing angular character of "peckhamite" and illustrating fragmental character of stone.
 4. Section showing angular character of pyroxene. This figure from the same slide as 2.
 5. Section showing angular character and frayed borders of the larger pyroxenes.

¹ It is interesting to compare this view with that expressed by others. Doctor Wadsworth (Lithological Studies, pp. 92-101) says: "I can find no evidence in the sections that its materials ever held any other relation than the present one and no sign of a former fragmental state, etc." Meunier (Memoirs, Nat. Acad. Sciences, vol. 13, p. 181), wrote: "We may suppose that the original mass was in a fragmentary state, partly stony, partly metallic, perhaps accumulated in a crevice, and was there subjected to metalliferous emanations whose product, in the form of a fine network, cemented these independent elements. The remarkable cavities sometimes occurring between the grains of iron and their stony matrices have been artificially reproduced in experiments on the metallic cementation of the powder of peridot by a process previously described." I do not infer from this that Meunier considered the rock *clastic in the sense that I am now claiming*.

² See Merrill, Geo. P. The Composition and Structure of Meteorites Compared with that of Terrestrial Rocks. Smithsonian Report for 1917, pp. 175-188, with 9 plates.

PLATE 23.

ESTHERVILLE, IOWA, METEORITE.

- FIG. 1. Micro-section showing general structure. The colorless areas with very irregular borders and no cleavage are anorthite. The black are metal and metallic sulphide; others olivines and pyroxenes.
2. The same under somewhat higher magnification and showing feldspars with clouded interiors and clear borders.
 3. The same showing a single feldspar in matrix of pyroxenes. Note the rounded form of nucleal portion of the feldspar and the bubbles projecting from this portion into the clear border. The crystal extinguishes as a unit with the exception of a portion of the margin, at the lower right.

PLATE 24.

ESTHERVILLE, IOWA, METEORITE.

Polished slice in cabinet of University of Minnesota. Approximate dimensions 20 by 33 cm. 1 and 2, pebble-form masses of enstatite; 3, pebble-form mass of 'peckhamite'; 4, metal; 5, cavities.